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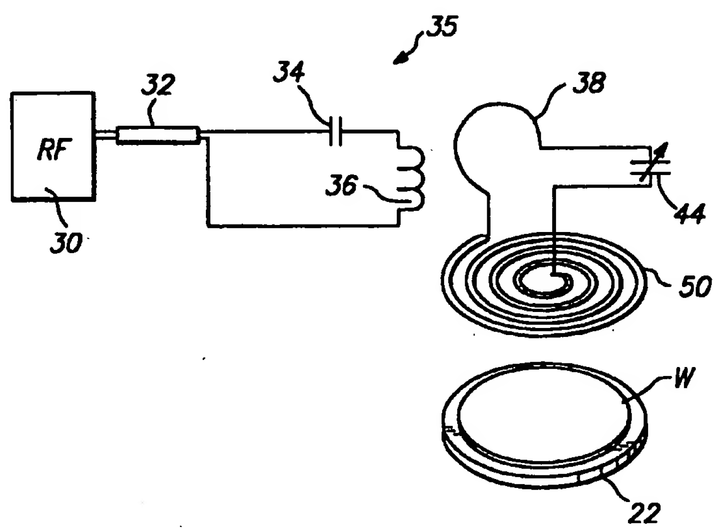
(54) Title: LOW INDUCTANCE LARGE AREA COIL FOR AN INDUCTIVELY COUPLED PLASMA SOURCE



(57) Abstract

A low inductance large area coil (LILAC) is provided as a source for generating a large area plasma. The LILAC comprises at least two windings which, when connected to an RF source via impedance matching circuitry, produce a circulating flow of electrons to cause a magnetic field in the plasma. Because the LILAC employs multiple windings, few turns of winding are required to obtain a large area coil, so that the inductance of the LILAC is low. The low inductance of the LILAC ensures that the self-resonating frequency of the LILAC is kept at a level far above the RF driving frequency, allowing a broad frequency range for impedance matching. Thus, there is no difficulty in impedance matching, and power transfer can be maximized, permitting efficient generation of a large area plasma.

LOW INDUCTANCE LARGE AREA COIL FOR AN INDUCTIVELY COUPLED PLASMA SOURCE

BACKGROUND OF THE INVENTION

The present invention relates generally to a low inductance large area coil for an inductively coupled plasma source. More specifically, the present invention relates to a low inductance large area coil as a source for generating a plasma which can be used for treating semiconductor wafers in low pressure processing equipment.

Plasma generation is useful in a variety of semiconductor fabrication processes, for example enhanced etching, deposition, etc. Plasmas are generally produced from a low pressure gas by inducing an electron flow which ionizes individual gas molecules through the transfer of kinetic energy through individual electron-gas molecule collisions. The electrons are commonly accelerated in an electric field, typically a radio frequency (RF) electric field.

Numerous methods have been proposed to accelerate the electrons in the RF electric field. One method is to excite electrons between a pair of opposed electrodes which are oriented parallel to the wafer in a processing chamber. The use of an electric field normal to the wafer does not provide efficient conversion of the kinetic energy to ions, since a large portion of the electron energy is dissipated through electron collisions with the walls of the processing chamber or with the semiconductor wafer itself.

A more efficient technique for exciting electrons in the RF field is to use a single winding coil (SWC) parallel to the plane of the wafer and the plasma to excite the electrons. U.S. Patent No. 4,948,458 discloses a device for employing such a technique, which is depicted in Figures 1-3. As shown in Figure 1, a plasma generating device includes an enclosure 10 with an access port 12 formed in an upper wall 14. A dielectric shield 16 is disposed below the upper wall 14 and extends across the access port 12. The dielectric shield 16 is sealed to the wall 14 to define a vacuum-tight interior of the enclosure 10. A planar single winding coil (SWC) 20 is disposed within the access port 12 adjacent the dielectric shield 16 and oriented parallel to the wafer W which is supported by a

surface 22. A process gas is introduced into the chamber 18 through a port 24 formed on side of the enclosure 10.

Figure 2 depicts schematically the plasma generating device illustrated in Figure 1. As shown in Figures 1 and 2, an RF source 30 is coupled via a coaxial cable 32 through an impedance matching circuit 35 to the SWC 20. The impedance matching circuit 35 includes a primary coil 36 and a secondary loop 38 which may be positioned to adjust the effective coupling of the circuit and allow for loading of the circuit at the frequency of operation, thereby maximizing power transfer. The primary coil 36 is mounted on a disk 40 which may be rotated about a vertical axis 42 in order to adjust the coupling. A tuning capacitor 44 is provided in series with the secondary loop 38 to adjust the circuit resonant frequency to the RF driving frequency. Another capacitor 34 is provided to cancel part of the inductive reactance of the primary coil 36 in the circuit. By resonating an RF current at a resonant frequency tuned to typically 13.56 Mhz through the coil 20, a planar magnetic field is induced, which penetrates the dielectric shield 16. The magnetic field causes a circulating flow of electrons between the coil 20 and the wafer W. The circulating flow of electrons makes it less likely that the electrons will strike the enclosure wall 10 between the coil 20 and the wafer W, and since the electrons are confined to a plane parallel to the planar coil 20, the transfer of kinetic energy in non-planar directions is minimized.

Shown in detail in Figure 3, the SWC 20 comprises a singular conductive element formed into a planar spiral or a series of concentric rings. As shown in Figures 1 and 3, the SWC 20 also includes a center tap labeled (+) and an outer tap labeled (-), so that it can be connected to the circuitry of the plasma generating device.

In certain applications, such as the production of 400 mm wafers or large area flat panel displays, a large area plasma is needed. In order to produce a large area plasma, the area or diameter of the SWC 20 shown in Figures 1-3 must be increased. For a fixed pitch between turns, the SWC 20 increases in inductance if turns are added to increase the diameter. At large diameters, the

SWC 20 produces a high inductance, which reduces the self-resonating frequency of the SWC 20. As the self-resonating frequency becomes nearer the radio frequency (RF) driving frequency, which is normally 13.56 MHz, impedance matching becomes more and more difficult. This is because it is hard to exactly match impedance within a small frequency range, due to the increased sensitivity of the match condition to changes in the settings of the impedance matching components. Therefore, a difficulty arises in maximizing power transfer when using an SWC to generate a larger area plasma.

SUMMARY OF THE INVENTION

The invention provides an apparatus for generating an inductively coupled plasma, the apparatus comprising an enclosure surrounding a plasma reaction chamber bounded by a dielectric shield, an inlet in the enclosure supplying a process gas into the chamber, a coil comprising at least two electrically conductive windings disposed outside the enclosure proximate the dielectric shield, and a radio frequency source coupled to the windings via impedance matching circuitry which matches the impedance of the radio frequency source to the windings and a frequency tuning mechanism which provides resonance, the radio frequency source being effective to resonate a radio frequency current in the coil and excite the process gas into a plasma within the chamber.

According to various aspects of the invention, the coil can have different configurations. For instance, the windings can be parallel and in the same plane, the coil can be non-planar, the windings can be connected together at opposite ends thereof, the windings can be unconnected together at opposite ends thereof, the windings can be interleaved, the windings can be non-interleaved but cover different surface areas and/or the turns of one of the windings are separated by the turns of the other one of the windings. The enclosure can comprise a multiple or single wafer etching apparatus wherein a wafer chuck supports one or more semiconductor wafers having a surface to be processed parallel to the plane of the coil.

The invention also provides a method for generating an inductively coupled plasma, the method comprising the steps of introducing a process gas into a plasma reaction chamber enclosed by an enclosure bounded by a dielectric shield, and resonating a radio frequency current in a coil comprising at least two electrically conductive windings disposed outside the enclosure proximate the dielectric shield, the radio frequency current being effective to excite the process gas into a plasma within the chamber.

The method can be carried out using the various coil configurations mentioned above. Further, the plasma can be used to process one or more substrates such as semiconductor wafers or flat panel displays. For instance, a semiconductor wafer can be located in the chamber and a layer on the wafer can be etched by the plasma. During processing, the chamber can be maintained at a wide range of pressures but in a preferred embodiment the pressure is maintained below 100 mTorr.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts a plasma generating device employing a conventional single winding coil.

Figure 2 illustrates schematically a plasma generating device employing a conventional single winding coil.

Figure 3 illustrates in detail a conventional single winding coil.

Figures 4A and 4B show comparisons between a conventional single winding coil and a double winding coil according to the present invention.

Figure 5 depicts an interleaved double winding coil according to one embodiment of the present invention.

Figure 6 depicts a non-interleaved multiple winding coil according to another embodiment of the present invention.

Figure 7 depicts a plasma generating device employing a low inductance large area coil according to the present invention.

Figure 8 illustrates schematically a plasma generating device employing a low inductance large area coil according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a low inductance large area coil (LILAC) with multiple windings which, when connected to an RF source, efficiently generates a large area plasma. Since the LILAC has multiple windings, fewer turns of winding are required to obtain a large diameter than if only one winding were used, as in a single-winding coil. Fewer turns of winding creates less inductance, which keeps the self-resonating frequency of the LILAC high, well above the normal 13.56 MHz RF driving frequency. The broad frequency range between the self-resonating frequency of the LILAC and the RF driving frequency enables accurate impedance matching, ensuring a maximum power transfer and an efficient generation of plasma.

According to the present invention, a low inductance large area coil (LILAC) is provided as a source for generating a large area plasma. The LILAC comprises at least two windings which, when connected to an RF source via impedance matching circuitry, produce a circulating flow of electrons to cause a magnetic field in the plasma. Because the LILAC employs multiple windings, few turns of winding are required to obtain a large area coil, so that the inductance of the LILAC is low. The low inductance of the LILAC ensures that the self-resonating frequency of the LILAC is kept at a level far above the RF driving frequency, allowing a broad frequency range for impedance matching. Thus, there is no difficulty in impedance matching, and power transfer can be maximized, permitting efficient generation of a large area plasma.

Figures 4A and 4B illustrate a comparison between an SWC and a LILAC with the same diameter. In Figure 4A, the SWC 20 has four turns of winding with a pitch of 0.5 inches between conductors. The LILAC 50 in Figure 4B has the same diameter and same interconductor spacing as the SWC 20 in Figure 4A, but has two turns of each winding with a pitch of 1 inch. Since the LILAC 50 of the same diameter as the SWC 20 has half as many turns, the inductance of the LILAC is lower, which makes impedance matching easier at large diameters. Another reason that the LILAC inductance is low is

that some or all of the windings can be electrically connected in parallel and inductances connected in parallel have a lower net inductance than the individual inductors.

A simple double winding version of the LILAC is illustrated in Figure 5. Referring to Figure 5, the double winding LILAC 50 has a planar spiral geometry, with two windings in parallel. The pitch is doubled, relative to an SWC of the same diameter, with the windings interleaved to give a coil with about the same spacing between conductors as the SWC. The two windings are connected together at each end. A center tap (+) and an outer tap (-) facilitate connection to a plasma generating device.

Although in Figure 5, the ends of the windings are connected, the ends of the windings do not have to be connected. One or more of the windings can be shorter than another winding and connected to that winding at some other point than the end.

Alternatively, more than two interleaved windings may be used or the coil may be non-planar.

Figure 6 depicts another embodiment of the LILAC, in which there are four windings, and the windings are not interleaved. The windings have (+) taps in their respective centers and there is a (-) tap where the windings meet to facilitate connection to a plasma generating device. The four windings can cover different surface areas, similar to several SWCs in parallel. A LILAC using non-interleaved multiple windings to cover an area requires fewer turns than an SWC covering the same area. Thus, the non-interleaved LILAC configuration keeps inductance low and ensures an efficient large area plasma generation.

A plasma generating device employing the LILAC is depicted in Figures 7 and 8. The LILAC 50 may be simply powered by a single RF source 30 and an impedance matching circuit 35, like those used to power the SWC 20 as shown in Figures 1 and 2. Alternatively, although not illustrated, a complex LILAC design with multiple windings can employ multiple matching networks and generators.

The LILAC 50 described above permits efficient generation of a large area plasma. Although particular embodiments of the invention have been described, it will be appreciated by those of ordinary skill in the art that the present invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. For example, although a LILAC with two or four windings has been illustrated, the number of windings is not limited thereto, but may be any number which meets the demands of large area plasma generation. Also, although the LILAC has been described as the primary coil for plasma generation, it can also be used as an auxiliary coil in conjunction with a different primary coil. The presently disclosed embodiments are therefore considered in all respects to be illustrative, and not restrictive. The scope of the invention is indicated by the appended claims, rather than the foregoing description, and all changes that come within the meaning and range of equivalence thereof are intended to be embraced therein.

What Is Claimed Is:

1. An apparatus for generating an inductively coupled plasma, the apparatus comprising:

an enclosure surrounding a plasma reaction chamber bounded by a dielectric shield;

an inlet in the enclosure supplying a process gas into the chamber;

a coil comprising at least two electrically conductive windings disposed outside the enclosure proximate the dielectric shield;

a radio frequency source coupled to the windings via impedance matching circuitry which matches the impedance of the radio frequency source to the windings and a frequency tuning mechanism which provides resonance, the radio frequency source being effective to resonate a radio frequency current in the coil and excite the process gas into a plasma within the chamber.

2. The apparatus of Claim 1, wherein the windings are parallel and in the same plane or the coil is non-planar.

3. The apparatus of Claim 1, wherein the windings are connected together at opposite ends thereof or the windings are not connected together at opposite ends thereof.

4. The apparatus of Claim 1, wherein the windings are interleaved or the windings are not interleaved but cover different surface areas.

5. The apparatus of Claim 2, wherein the enclosure comprises a single wafer plasma etching apparatus and includes a wafer chuck supporting a semiconductor wafer, the wafer having a surface to be processed parallel to the plane.

6. The apparatus of Claim 2, wherein the turns of one of the windings are separated by the turns of the other one of the windings.

7. A method for generating an inductively coupled plasma, the method comprising the steps of:

introducing a process gas into a plasma reaction chamber enclosed by an enclosure bounded by a dielectric shield;

resonating a radio frequency current in a coil comprising at least two electrically conductive windings disposed outside the enclosure proximate the dielectric shield, the radio frequency current being effective to excite the process gas into a plasma within the chamber.

8. The method of Claim 7, wherein the windings are parallel and in the same plane or the coil is non-planar.

9. The method of Claim 7, wherein the windings are connected together at the ends thereof or the windings are not connected together at the ends thereof.

10. The method of Claim 7, wherein the windings are interleaved or the windings are not interleaved but cover different surface areas.

11. The method of Claim 7, wherein a semiconductor wafer is located in the chamber and a layer on the wafer is etched by the plasma.

12. The method of Claim 7, wherein the chamber is maintained at a pressure below 100 mTorr.

13. The method of Claim 7, wherein the windings lie in a plane and are separated from each other by a uniform distance.

14. A transformer coupled plasma inductor for use in forming a plasma gas in a plasma reaction chamber, comprising:

a planar coil comprising at least two electrically conductive windings, the coil being attachable to a plasma reaction chamber and capable of generating plasma gas of substantially uniform plasma density in a planar region of the plasma reaction chamber by resonating a radio frequency current in the coil.

15. The plasma inductor of Claim 14, wherein the windings are electrically connected together at opposite ends thereof.

16. The plasma inductor of Claim 14, wherein the turns of one of the windings are separated by the turns of the other one of the windings.

17. The plasma inductor of Claim 14, wherein the windings lie in a plane and are separated from each other by a uniform distance.

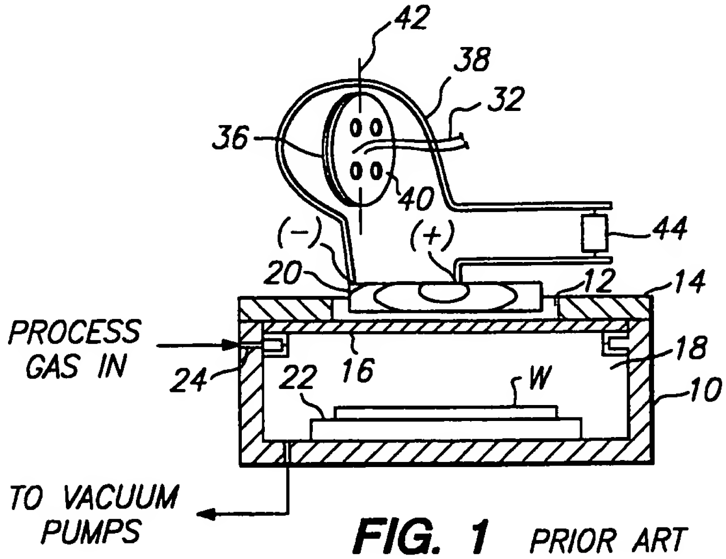


FIG. 1 PRIOR ART

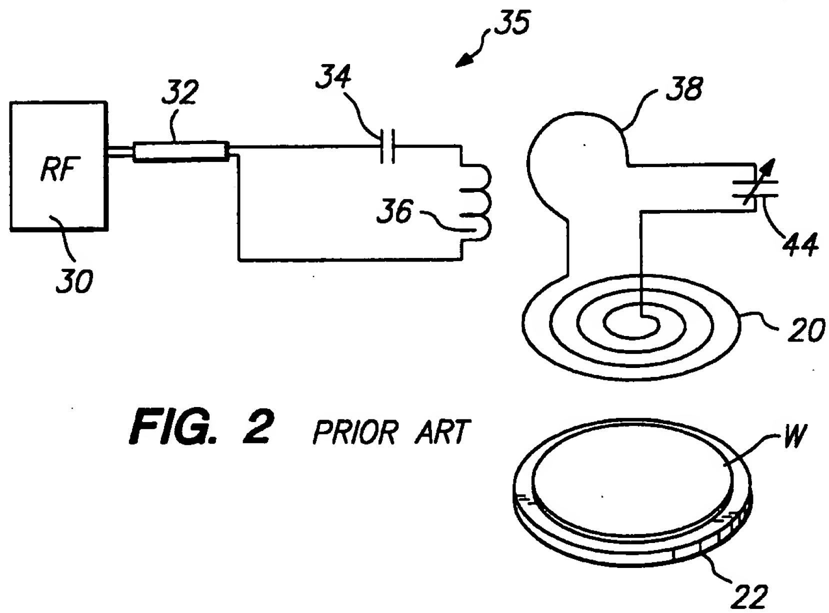


FIG. 2 PRIOR ART

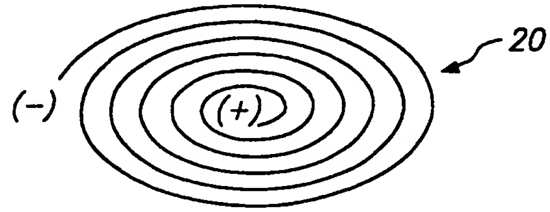


FIG. 3 PRIOR ART

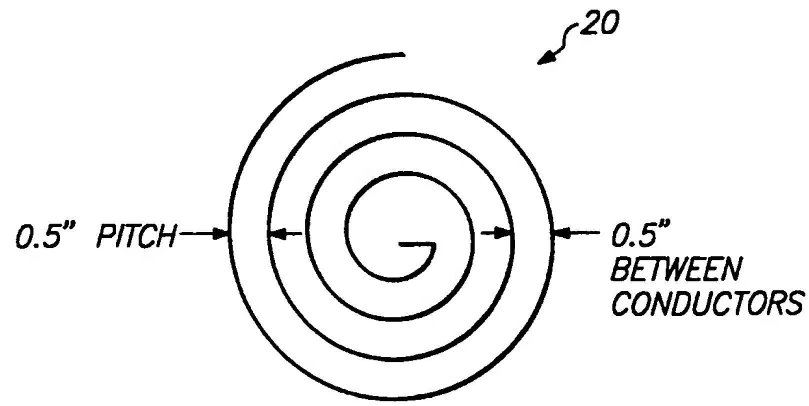


FIG. 4A
PRIOR ART

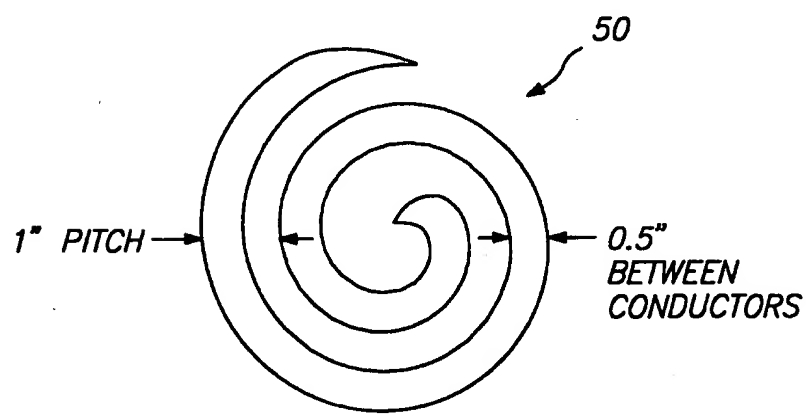


FIG. 4B

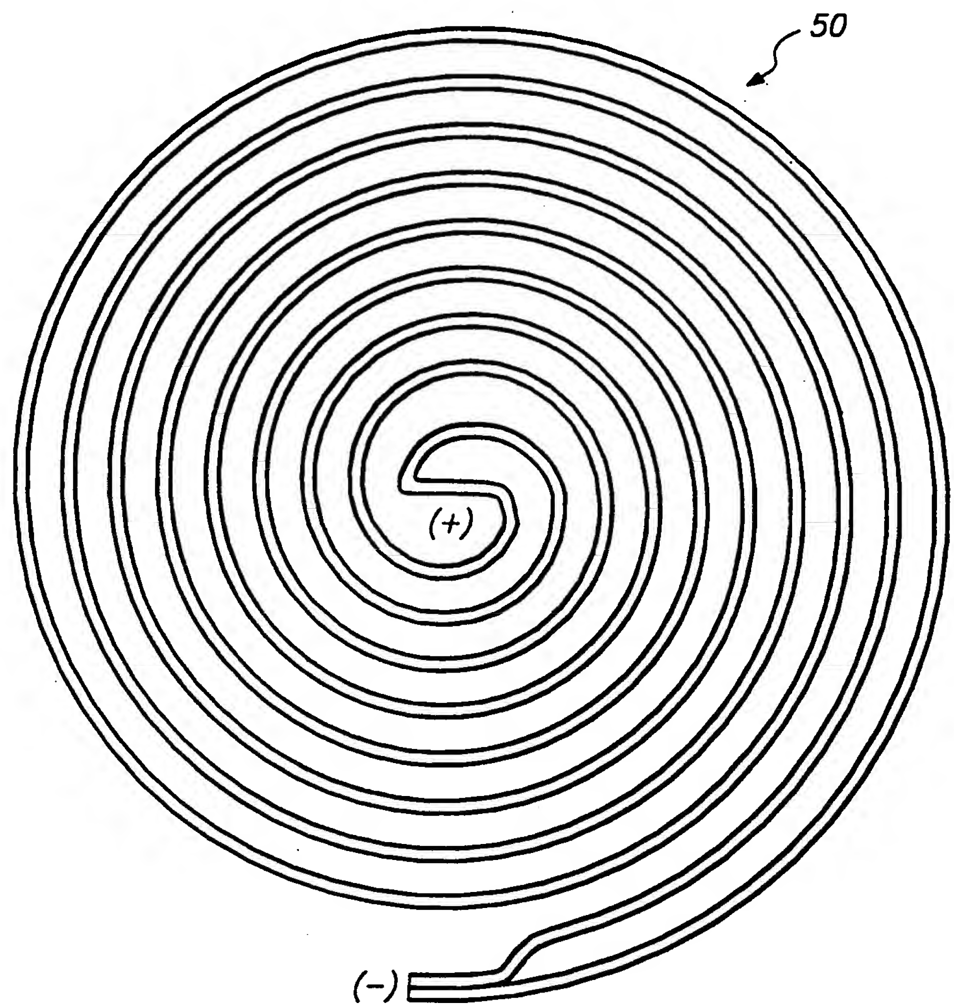


FIG. 5

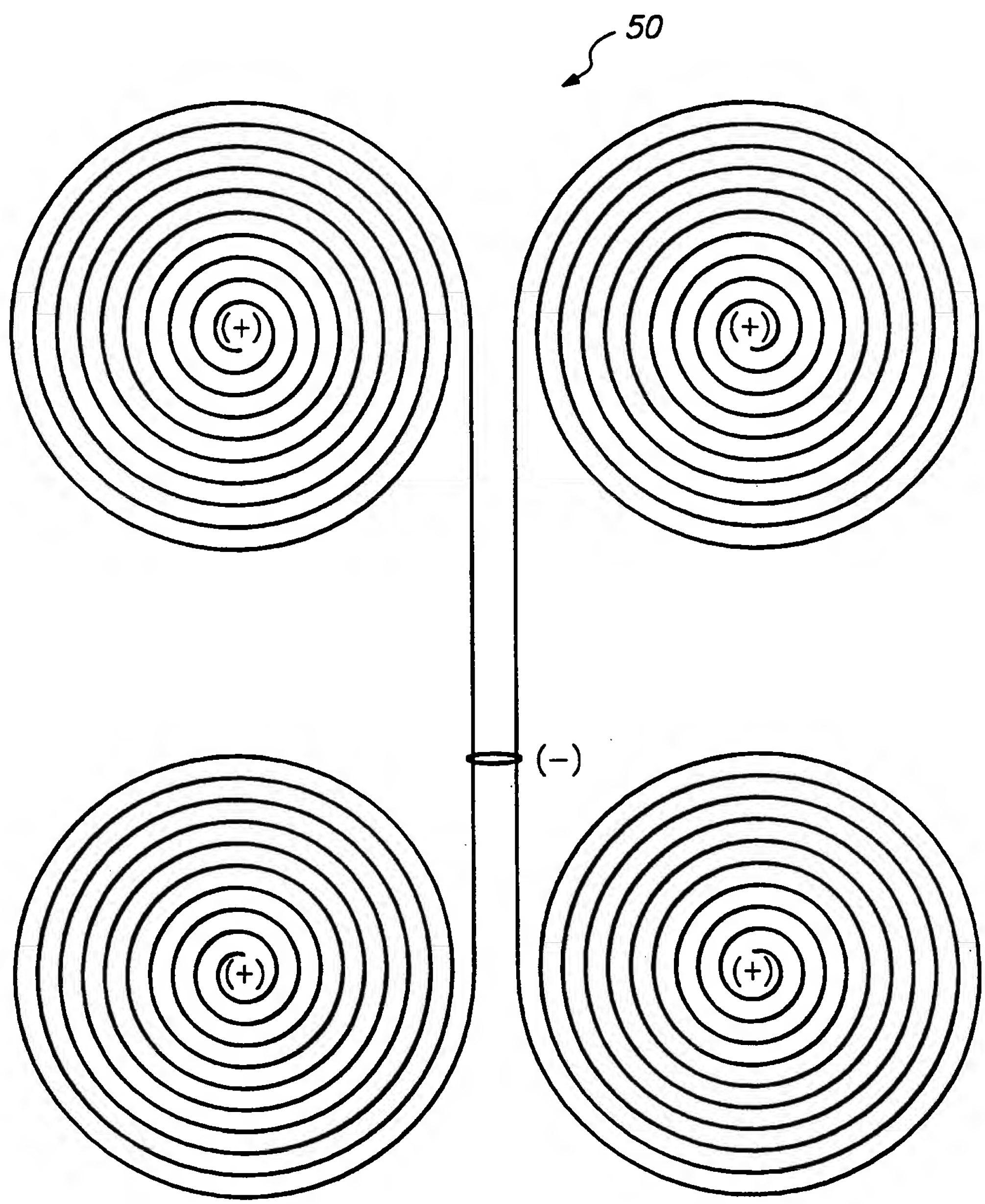


FIG. 6

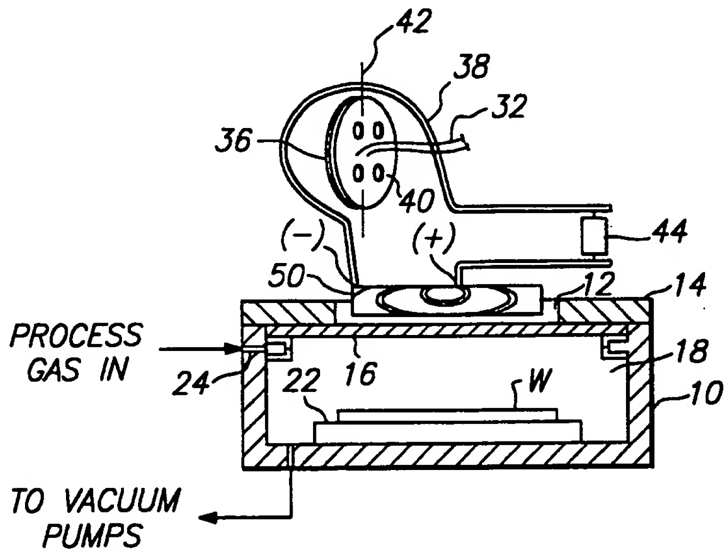

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FIG. 7

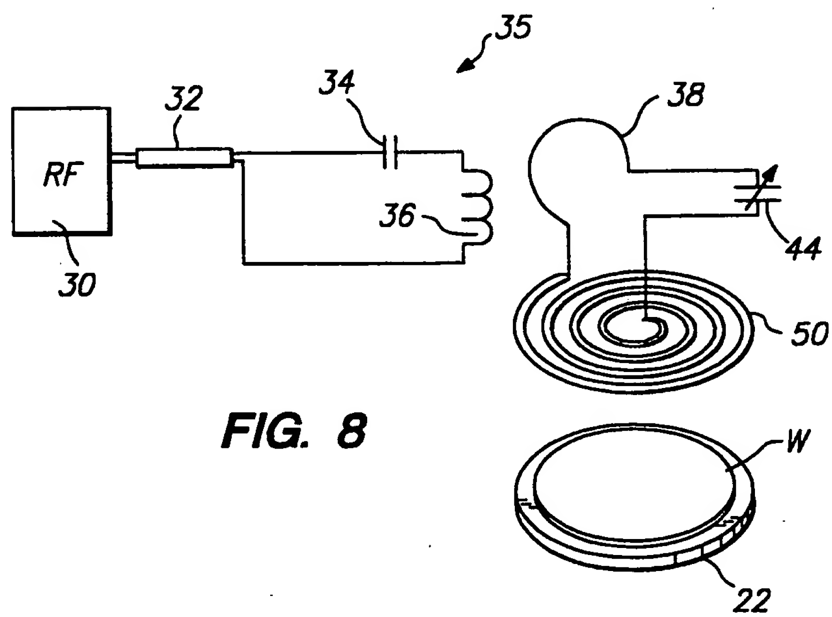
35
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FIG. 8

INTERNATIONAL SEARCH REPORT

In. ational Application No
PCT/US 96/10804

A. CLASSIFICATION F SUBJECT MATTER
IPC 6 H01J37/32 H05H1/46

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01J H05H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,5 401 350 (PATRICK ET AL) 28 March 1995 see column 2, line 57 - column 3, line 32 see column 4, line 63 - column 5, line 21 see column 8, line 42 - column 9, line 4 see figures 1-3,12,12A ---	1-17
X	US,A,5 405 480 (BENZING ET AL.) 11 April 1995 see column 2, line 41 - column 4, line 53; figures 1,2,5 ---	1-12
P,X	EP,A,0 710 055 (APPLIED MATERIALS, INC.) 1 May 1996 see page 4, line 50 - page 5, line 13; figures 3-5 --- -/--	1-17

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
14 October 1996	25.10.96
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Bergado Colina, J

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INTERNATIONAL SEARCH REPORT

In. ational Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	EP,A,0 694 949 (APPLIED MATERIALS, INC.) 31 January 1996 see column 3, line 51 - column 6, line 13; figures 1-5	1-12
P,X	JP,A,08 148 476 (SONY CORP.) 7 June 1996 see figures 1,2	1-17
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A	US,A,5 368 710 (CHEN ET AL.) 29 November 1994 see the whole document	1-17

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INTERNATIONAL SEARCH REPORT

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